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Research Paper

Dynamic analysis and reliability design of round baler feeding device for rice straw harvest

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The feeding device of steel-roll round baler provides an intermediate link between the compression chamber and the pickup device. A discrete element method (DEM) was used to simulate the rice straw feeding process. By differentiating the surface of jaw plate and analysing the force vector on each part, the forces on piston rod of lifting hydraulic cylinder were obtained by integral calculation. Exponential models for the mean force on piston rod and torque on feeding roller were established with increasing throughput. The displacement of piston rod represented the feed opening. When piston rod displacement was in the range 0–30 mm, there was a significant decrease in the mean values of force on the piston rod and torque on the feeding roller with increasing feed opening. This unloading effect was not obvious when the displacement exceeded 30 mm. To improve reliability, safety factors for the feeding device were calculated using FEM simulations at different values of displacement and throughput. The variation of mean force was determined with safety factor of 1.3. A hydraulic cylinder drive circuit was designed with an accumulator. Rice straw baling experiments were carried out and the performance was in basic agreement with the DEM simulations. The feed opening increased automatically once the straw throughput rate surged. This reduced the peak load, avoid blockage, and protected the feeding device. The relationship obtained between feeding load and straw throughput rate provides the basis for the design of an automatic control system for a baler.

1. Introduction

Rice is one of the most important food crops in China with the planting area is about 30 million ha. It produces more than 210 million tonnes rice and nearly 300 million tonnes of straw every year. As a source of renewable biomass energy, rice straw is widely used, for example, in papermaking, livestock feed, and bioethanol. However, high biomass harvesting cost is one of the constraints in popularising the comprehensive utilisation of straw (Khanna, Dhungana, & Clifton-Brown, 2008; Singh, 2016). Baling is a feasible method to collect, transport and store straw, and it has proved to be an effective way to reduce cost (Martelli, Bentini, & Monti, 2015).

Balers can be divided into round balers and square balers according to the working principle and the shape of straw bale

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Nomenclature

d	Diameters of piston rod, m
D	Diameters of inner cavity, m
F	Force on piston rod, N
$\mathbf{F}$	Force vector on each monitoring piece, N
F_G	Force component produced by gravity, N
F_S	Force component produced by straw, N
F_{S0}	Mean value of F, N
F_{Sn}	Harmonic component of F, N
$\mathbf{G}$	Gravity vector of jaw plate, N
k	Straw throughput rate, kg s^{-1}
$\mathbf{L}_{Gx}$	Moment arm vector of $\mathbf{G}$, m
$\mathbf{L}_{ix}$	Moment arm vector of $\mathbf{F}_i$, m
L_x	Moment arm of F, m
N	Safety factor
P_1	Oil pressure in no-rod cavity, MPa
P_2	Oil pressure in rod cavity, MPa
T	Torque on feeding roller, N m
T_0	Mean value of T, N m
T_n	Harmonic component of T, N m
x	Displacement of piston rod, m
σ_F	Fluctuation coefficient F
σ_T	Fluctuation coefficient T

(Pari et al., 2017; Shinners, Huenink, Muck, & Albrecht, 2009). Many studies have been carried out on the effect of operating parameters on baling performance, compressive mechanical properties of straw, monitoring and the automatic control technology of working status (Afzalinia & Roberge, 2008; Borreani, Bisaglia, & Tabscco, 2007; Li et al., 2017; Maraldi, Molari, Regazzi, & Molari, 2017). A round baler is a relatively economical harvesting platform. It is light and provides good floatation on soft rice fields. It also has a low power requirement and can form variable density compact core bales (Hirokatsu, Nobuki, Yukinori, & Kimiyasu, 2006; Lavoie, Savoie, D'Amours, & Joannis, 2008; Womac, Hart, Bitra, & Kraus, 2012). An important task is to improve the in-field yield variability of throughput which results in lower biomass cost. At present, adjusting the ground speed of machines to maximise throughput in relation to yield is the main method adopted, and various types of biomass yield sensing in front of a baler have been explored to predict throughput (Lenaerts, Missotten, Baerdemaeker, & Saeys, 2012; Mathanker, Maughan, Hansen, Grift, & Ting, 2014). Among yield sensors, those based on light detection and ranging (LIDAR) are the most widely used.

Rice straw baling is carried out in the field after the grain harvest by combine harvester is finished. It is influenced by the variabilities of stubble height, soft uneven field and the straw throwing states of combine harvesters. It therefore becomes a challenge to accurately predict straw yield in front of the baler in real-time. Furthermore, straw throughput is also affected by the efficiency of the pickup device. Even at the same throughput, variations in the physical properties of straw such as length and moisture content will also changes the dynamic process of bailing (Han, Collins, & Vanzant, 2004; Savoie, Hébert, Robert, & Sidders, 2013). These challenges result in larger fluctuations in predictions, especially in small and medium-sized paddy fields. The smaller throughput the lower operating efficiency and the higher the biomass cost. Yet, increasing the straw throughput easily leads to overloading and blockage, even causing structural deformation or damage. Blockage often occurs in the feeding device which is one of the important problems in the operation of small and medium-sized round balers (Wang, Jiang, & Wang, 2010). Therefore, improving operating efficiency to avoid blockage and to ensure structural safety is an important issue.

Straw feeding is the intermediate link in baling operations, and its power consumption is an important part of the total power consumption of round baler (Freeland & Bledsoe, 1988). Understanding the dynamic characteristics of the feeding device is essential, because it can provide the basis for structural optimisation and automatic control system (Kumhála, Kroulík, & Prosek, 2007). The objective of this paper is to simulate the process of rice straw being fed into the compression chamber using the discrete element method (DEM), and analyse the influence of straw throughput and structural parameters on the load variations in the feeding device. According to load variations obtained by DEM simulation, the safety factor of the device was then calculated using FEM. An improved design of the oil system is then proposed to avoid blockage, improve operational efficiency and mechanism reliability. Finally, baling tests are conducted to verify the analysis results and to evaluate operating performance.

2. Materials and methods

Rice straw is a cylindrical form of agricultural material. The properties such as mass, diameter and lengths are influenced by varieties, seasons and grain harvesting methods. It is the basis of dynamic analysis to calculate the load variation accurately according to the material characteristics, device structure and operation parameters.

2.1. Equipment

The equipment used in this investigation is a World WDB800 (Jiangsu World Agricultural Machinery Co., Ltd., Zhenjiang, China) steel-roll round baler (Fig. 1). It consists of a frame,

Fig. 1 – WDB800 steel-roll round baler.